"WVU's contribution within the ZAPP collaboration on the Z Facility at Sandia National Laboratories"

DE-SC0012515

Prof. Mark Koepke, PI

Final Technical Report

Abstract:

In **Year 1**, photoionized silicon spectroscopy experiments were designed and executed, with charge-state distribution and ionic column densities comparable to the circumsource environments of accretion-powered black holes. Charge-state distribution was measured with absorption spectroscopy, using the Z-pinch itself as backlight, and the photoionizing radiation flux was determined with x-ray power measurements, accounting appropriately for geometrical dilution. The emergent emission spectrum was measured with a high-sensitivity time-integrated spectrometer. The emission has been measured from plasmas with varying size to elucidate the radiation transport effects. Data and knowledge of the controlled experimental conditions were provided to collaborators who used different atomic kinetics spectral synthesis codes to predict the emission spectrum. In **Years 2 and 3**, multi-element (in layers) foil was used for diagnostic development. A framing mask was implemented into the configuration to aperture the radiation incident on the foil. The foil distance from the z-pinch was adjusted to achieve designed electron temperature and ultimately mounted directly on the Return-Current Cannister. A much higher ionization state was achieved, which is desirable for diagnostic development. In **Year 4**, significant data analysis took place. Astrophysics related projects were introduced "Seeking a full theory of Stark broadening at HED in the presence of crossed E and B fields for estimating surface gravity from line profiles in Magnetic White Dwarf (MWD) stars" and "Plasma collective effects in atomic kinetics calculations of lineshape, line position, and line amplitude" for inclusion into the ZAPP collaboration, but were declined by ZAPP leadership. During the grant period, WVU contributed to three proposals for a ZAPP Center of Excellence that were prepared and/or submitted in part or in full. **(1)** NSF Physics Frontier Center solicitation 16-561, PI / Director: A. Wootton, UTexas, "Center for experimental astrophysic"s (declined), **(2)** NSF Science and Technology Center solicitation 2017, PI/Director: D. Winget, UTexas, "Formation and Evolution of Planets, Stars and Galaxies and Extreme-Parameter Laboratory Astrophysics" (awaiting restoration of the solicitation after unexpected postponement), and **(3)** NNSA Stewardship Science Grant Program solicitation 81-112, PI/Director: D. Winget, UTexas, "Center for Astrophysical Plasma Properties" (submitted in 2017, awarded in 2018). Based on the work performed during the grant period, a new **NNSA grant application** to support a WVU project in ZAPP, "Spectroscopic methods to obtain electron density and electron temperature applied to soft x-ray absorption spectra from radiatively heated Z-pinch plasmas", was submitted in 2017 and funded in 2018.

Activities prior to grant:

D. Winget invited M. Koepke to join the ZAPP collaboration in 2012. In 2013, M. Koepke was installed as the university lead on the ZAPP project "X-ray line formation in radiation-dominated astrophysical plasmas" that was carried out by a team consisting of D Liedahl (LLNL), J Bailey (SNL), G Loisel (SNL), and M Koepke (WVU).

The Z Astrophysical Plasma Properties (ZAPP) collaboration [Montgomery et al., 2012] was granted ten Z shots/year during calendar years 2011-2013. In 2013, a one-year pause in the ZAPP collaboration suddenly took place and eventually ended, re-enabling Z to be used for fundamental science by the academic community (WVU contributed to preparing the facility-access letter in support of this re-enabling). An additional 5-10 Z shots/year, starting in calendar year 2014, were made available to drive

the ZAPP collaboration, including the Resonance Auger Destructions experiments that comprised "X-ray line formation in radiation-dominated astrophysical plasmas (M. Koepke, W. Virginia Univ., lead)", the primary theme of M. Koepke's grant application to the NSF-DOE Partnership in Basic Plasma Physics and Engineering, "WVU's contribution within the Z astrophysical plasma properties (ZAPP) collaboration on the Z Facility at Sandia National Labs" (this grant). Each ZAPP project uses diagnostics that are mutually compatible and that can support simultaneously all four projects on the same shot.

Letter re-enabling facility time for the ZAPP collaboration:
Date: November 19, 2013

To: Dr. James Bailey
Sandia National Laboratories

From: Mark Herrmann, Pulsed Power Sciences Center
Sandia National Laboratories

Subject: Notification of allocation of fundamental science experiments on Z.

We have now nearly completed the first three years of the fundamental science program on the Z facility. Following the call for proposals, an external program review committee chaired by Dr. Alan Wootton with members Prof. Nathaniel Fisch, Prof. Dario Alfe, Prof. Yitzak Maron, Dr. Didier Saumon, and Dr. Pravesh Patel met and reviewed the submitted proposals. All committee members were asked to read all proposals and submit comments and score the proposals according to three criteria:

1. Scientific and technical soundness and quality of the proposed method/approach, and the feasibility/likelihood of accomplishment of the stated objective.
2. The overall scientific/technical merit of the project and its relevance and prospective contribution to its field of research.
3. The competence, experience, and past performance of the applicant, principal investigator and/or key personnel.

As you know, your proposal, "Laboratory tests of stellar interior opacity models", was favorably reviewed and you were awarded time on the Z facility in CY11, CY12, and CY13. Based on the exciting progress you and the members of your collaboration have been making we have awarded you additional time on the Z facility in CY14. The award consists of hardware necessary to field the experiment, days on the facility, and the time of Sandia scientists who are participating in your project.

The platform used in the experiments you have proposed is capable of supporting several ride-along experiments probing important scientific questions. In particular work by Professor Pradhan, "Validating theoretical stellar interior and HED plasma opacities at the Sandia Z", Professor Mancini, "Photoionized plasmas in astrophysical warm absorbers", Professor Winget, "Spectral Line-Broadening in White Dwarf Photospheres", Dr. Liedahl, "X-ray Line Formation in Radiation-Dominated Astrophysical Plasmas", and Prof. Koepke "WVU's contribution within the Z astrophysical plasma properties (ZAPP) collaboration on the Z Facility at Sandia National Laboratories" can be supported in a ride along mode with your experiments. Please work with Prof. Pradhan, Prof. Mancini, Prof. Winget, Dr. Liedahl, and Prof. Koepke to help them perform the exciting research that they have outlined using your time on the Z facility.

Both the shot days awarded and your time are a precious resource. We are committed to working in close collaboration with you to ensure the success of these exciting experiments. Experience has shown the biggest contributor to the success of experiments on the Z facility is careful planning performed well in advance of the experiments. For each experimental series executed a series of three design reviews (Experimental Objectives Review, Initial Design Review, and a Final Design Review) will be held. Another contributing feature shared by past successful experiments is the commitment by the experimental team to spend substantial time on-site at the Z facility to prepare for the experiment.

Planning for experiments should incorporate platforms, diagnostics and capabilities that are in place on the Z facility today. While we anticipate the platforms, diagnostics, and capabilities for Z will advance over time, requiring new capabilities for an experimental series is likely to lead to substantial delays in our ability to execute the experiments.

The experiments you proposed are ambitious and a novel application of the unique capabilities of the Z facility to problems of fundamental scientific interest. We are looking forward to collaborating with you on this exciting work.

Sincerely,
Mark Herrmann, Director
Pulsed Power Sciences Center, Sandia National Laboratories, Albuquerque, NM
Work: 505 284 0236, Blackberry: 505 264 9033, mherrma@sandia.gov

Project Summary:

Over the course of the grant:

1. Photoionized silicon spectroscopy experiments were designed and executed, with charge-state distribution and ionic column densities comparable to the environments of accretion-powered black holes. Silicon-foil targets allowed us to attain astrophysically relevant values of column densities. Implementing a transition from image plates to x-ray film (Kodak DEF and Kodak 101-07) increased signal-to-noise ratio (photographic response) by an order of magnitude.

2. Charge-state distribution was measured with absorption spectroscopy, using the Z-pinch itself as backlight. The photoionizing radiation flux was determined with x-ray power measurements, accounting appropriately for geometrical dilution.

3. The emergent emission spectrum was measured with a high-sensitivity time-integrated spectrometer. The emission has been measured from plasmas with varying size to elucidate the radiation transport effects.

4. Data and knowledge of the controlled experimental conditions for silicon were provided to collaborators who used different atomic kinetics spectral synthesis codes to predict the emission spectrum. Results were published in a peer-reviewed journal.

5. A show-stopping risk to the ZAPP collaboration emerged when G. Loisel's 3-year time limit associated with his ZAPP-postdoc appointment was fast approaching. A ZAPP-postdoc supplement to the parent award was submitted and awarded (which supported P. Kozlowski in Years 3 and 4) while attempts to change the postdoc appointment-limit policy were initiated. The policy change was eventually implemented. The combined strategy achieved its goal, as G. Loisel was ultimately converted to staff having approximately 50% full-time effort on ZAPP about the time that P. Kozlowski was on-boarded.

6. Multi-element (in layers) foil were used for diagnostic development. A framing mask has been implemented into the configuration to aperture only the Z-pinch radiation incident onto the foil.

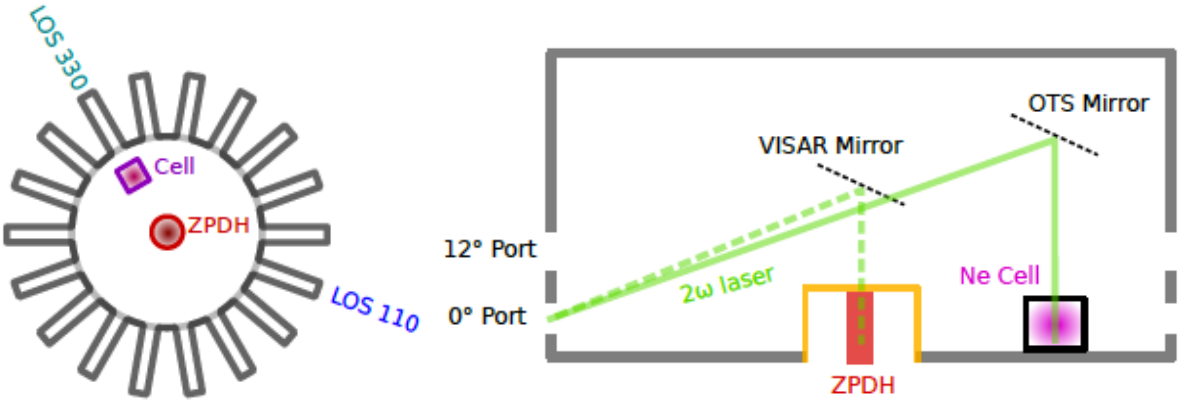
7. The foil was placed at a specific distance from the pinch in order to achieve designed electron temperature. Foil was mounted directly on the Return-Current Cannister and a much higher ionization state was achieved, which is desirable for diagnostic development.

8. Both iso-element and iso-electronic lines were observed and both sets of line ratios exhibit were found to depend on temperature for some range but not density. However, ratios originating from iso-electronic lines were found to vary more with change in temperature and are not as independent on density as ratios originating from iso-element lines.

9. Implementing and using Optical Thomson Scattering was found to be feasible as an electron temperature diagnostic for photoionized Neon experiments on Z. Results were published in a peer-reviewed journal after the grant period ended.

The project began with the objective to experimentally document the presence or absence of resonant Auger destruction (RAD) using a 26-MA Z-pinch-generated x-ray continuum-spectrum source to irradiate a gas cell containing silicon. For over one year, we measured Silicon emission and absorption spectra from the L-shell ions to test the validity of the astrophysical assumptions and to provide a new class of spectral diagnostics for black-hole spectroscopy. RAD is a hypothesized line-destruction mechanism that exists only at relatively high-energy-density and that involves the complex interplay of atomic kinetics and radiation transport. RAD has been invoked to explain the apparent absence of emission from L-shell ions in x-ray spectra of accretion-powered black holes. The predicted efficiency of RAD is contradicted by observations of neutron-star accretors in our own galaxy. A new priority arose in the Z Astrophysical Plasma Properties (ZAPP) collaboration and, after one year, the research objective was changed by Sandia to quantify consistency of determining electron temperature and electron density from a soft x-ray absorption spectrum. An iso-electronic line-ratio technique in absorption was tested as an electron temperature diagnostic for high-energy-density laboratory plasmas. Data was acquired on multielement Stark broadening to diagnose electron density. Five WVU grad students and one WVU postdoc participated in the project. Two off-campus research experiences (OCRE) were carried out by T. Lane (WVU graduate student) to Imperial College-London's MAGPIE, which resulted in two papers. Four peer-reviewed journal articles were published.

Optical Thomson Scattering is feasible as a diagnostic on Z:



Left: Top view of the Z chamber displaying the 18 radial LOS ports. The TREX diagnostic for the Ne gas cell experiments is along LOS 330 (green). Gas Cell (purple) sits inside chamber at some radial offset from the ZPDH (red). VISAR beam enters via LOS 110 (blue).
Right: Radial view of the Z chamber displaying the 0º and 12º inclination ports. VISAR beam (dashed green) will enter via on LOS 110 and will be reflected vertically into the central pinch region with a disposable mirror.
OTS diagnostic requires a different mirror configuration to reflect the CHACO laser (solid green) into the Ne gas cell (purple). Unlike the VISAR mirror, the OTS mirror does not need to be positioned directly above the pinch, nor does it need to view the pinch, and therefore it can be shielded to reduce costs.

-Plasma density is diagnosed using a pressure sensor.
-Charge-state distribution: X-ray absorption spectroscopy.

-Electron temperature is inferred from a Li-like ion level population ratio.
-OTS diagnoses T_e independently by directly probing f(v) while avoiding errors in T_e obtained via line ratio techniques caused by photoionization altering the charge state distribution.
-CHACO laser parameter range suits the application (an Nd:YAG laser, part of the Z-Backlighter Laser).
-Co-injection onto an existing beamline is more economical than building a new, dedicated beamline.
-VISAR is currently being constructed to enter the target chamber through LOS 110 at a 0^o inclination port. Provided that the optics can support the CHACO laser without being damaged (due to the larger energy requirements for OTS over VISAR), this beamline would be a good candidate for co-injection as the beginning of the beamline sits only a few feet away from the CHACO laser.
-Based on our simulations, it is possible to tune the CHACO laser down to the appropriate energy level for simultaneously mitigating heating by the probe and maximizing signal, such that it can be measured by the streaked visible spectroscopy (SVS) instruments.

Overall productivity

Personnel:

West Virginia University Graduate Students
Theodore S. Lane, West Virginia University, FTE = 1.0
Matthew K. Flaugh, West Virginia University, FTE = 0.0
Thomas Steinberger, West Virginia University, FTE = 0.0
Cuyler Beatty, West Virginia University, FTE = 0.0
David Dunkum, West Virginia University, FTE = 0.0

West Virginia University Postdoc
Pawel Kozlowski, FTE = 1.0, 28 Sept 2016 - 15 Feb 2018. Presently a postdoc at LANL P-24.

Principal investigator: Mark Koepke, West Virginia University

Publications related to this grant:

Benchmark experiment for photoionized plasma emission from accretion-powered x-ray sources, G. P. Loisel, J. E. Bailey, D. A. Liedahl, C. J. Fontes, T. R. Kallman, T. Nagayama, S. B. Hansen, G. A. Rochau, R. C. Mancini, and R.W. Lee, *Phys. Rev. Lett.* 119, 075001 (2017).

Feasibility Study for Implementing an Optical Thomson Scattering System for Studying Photoionized Plasmas on Z, P.M. Kozlowski; R.C. Mancini; M.E. Koepke, *IEEE Transactions on Plasma Science* 46, 3912 – 3921 (2018).

The structure of bow shocks formed by the interaction of pulsed-power driven magnetised plasma flows with conducting obstacles, G.C. Burdiak, S.V. Lebedev, S.N. Bland, T. Clayson, J. Hare, L. Suttle, F. Suzuki-Vidal, D.C. Garcia, J.P. Chittenden, S. Bott-Suzuki, A. Ciardi, A. Frank and T.S. Lane, *Phys, Plasmas* 24, 072713, 2017.

Ion heating and magnetic flux pile-up in a magnetic reconnection experiment with super-Alfvénic plasma inflows, L.G. Suttle, J.D. Hare, S.V. Lebedev, A. Ciardi, N.F. Loureiro, G.C. Burdiak, J.P. Chittenden, T. Clayson, J.W.D. Halliday, N. Niasse, D. Russell, F. Suzuki-Vidal, E. Tubman, T. Lane, J. Ma, T. Robinson, R.A. Smith, and N. Stuart, *Phys. Plasmas* 25, 042108 (2018). https://doi.org/10.1063/1.5023664.

Invited Presentations related to work funded by this grant:

M. Koepke, Interrelationship between lab, space, astrophysical, magnetic-fusion, and inertial-fusion plasma experiments, (plenary talk), 29th Summer School and International Symposium on the Physics of

Ionized Gases (SPIG 2018) held in Belgrade, Serbia, 28 August 28 - 1 September 2018 at the Serbian Academy of Sciences and Arts.

M. Koepke, “2014 Fusion Energy Sciences Advisory Committee (FESAC) Strategic Planning Panel Report” (invited talk), Plasma Physics Division Colloquium, Naval Research Laboratory, Washington, DC, 11 February 2015.

M. Koepke, “Partnering on Grand-Challenge Opportunities at the Fusion-Energy-Science Frontiers” (invited talk), Special Presentation in Photon Science Seminar Series, SLAC National Accelerator Laboratory, 18 March 2015.

T. Lane, M. Flaugh, M. Koepke, G. Loisel, G. Rochau, J. Bailey, “X-ray drive characterization - Experiment: What can we learn from the LTE opacity platform: Experiment design” (invited talk), RAD in Photoionized Silicon Workshop, Sandia National Laboratories, Albuquerque, NM, 30-31 March 2015.

M. Flaugh, T. Lane, M. Koepke, G. Loisel, G. Rochau, J. Bailey, “X-ray drive characterization - Modeling: What can we learn from the LTE opacity platform: Results” (invited talk), RAD in Photoionized Silicon Workshop, Sandia National Laboratories, Albuquerque, NM, 30-31 March 2015.

M. Koepke, G. Rochau, G. Loisel, J. Bailey, D. Liedahl, T. Nagayama, R. Mancini, T. Lane, M. M. Flaugh, “Absorption and Emission Spectroscopy Revealing Astrophysical Plasma Properties in At-Parameter Laboratory Simulations” (invited talk), IEEE-ICOPS, Antayla, Turkey, 24-29 May 2015.

M. Koepke, G. Loisel, G. Rochau, J.E. Bailey, T. Lane, M. Flaugh, “Partnering on Grand-Challenge Opportunities at the Fusion-Energy-Science Frontiers: the Z Astrophysical Plasma Properties Collaboration” (invited talk), 3rd Conference on Radiation from High Energy Density Plasmas, South Lake Tahoe, CA, 9-12 June 2015.

M. Koepke, “Opportunities at the Fusion-Energy-Science Frontiers: the Z Astrophysical Plasma Properties Collaboration” (invited talk), EPFL colloquium, Lausanne, Switzerland, 29 June 2015.

T. Lane, “Scientific Collaboration and Capability at the astronomical-observation and laboratory plasma Interface: The Z Astrophysical Plasma Properties (ZAPP) Collaboration” (invited talk), International Workshop on the Interrelationship between Plasma Experiments in the Laboratory and in Space, 23-28 August 2016, Pitlochry, United Kingdom.

M. Koepke, “Radiative properties measurements for stellar interiors and accretion powered objects” (invited talk), Plasma Physics Group Annual Conference, Institute of Physics (U.K.), Isle of Skye, UK, 22-26 May 2016.

Contributed Presentations related to work funded by this grant:

P. M. Kozlowski, T. S. Lane, M. E. Koepke, "Boltzmann plot techniques for inferring electron temperature of HED plasma" (contributed poster), Omega Laser User Group meeting, LLE, University of Rochester, Rochester, NY, 25-27 April 2018.

T.S. Lane, P.M. Kozlowski, G.P. Loisel, M.K. Flaugh, T.E. Steinberger, J. E. Bailey, G. A. Rochau, M.E. Koepke, Multi-element Stark broadening for diagnosing electron density in HED plasma, (contributed poster), Omega Laser User Group meeting, LLE, Univ. Rochester, Rochester, NY, 25-27 April 2018.

D.K. Dunkum, C.B. Beatty, T.S. Lane, P.M. Kozlowski, M.E. Koepke, G.P. Loisel, J. E. Bailey, G. A. Rochau, "Assessment of gradient effects on soft x-ray spectral measurements on the Z Machine" (contributed poster), Omega Laser User Group meeting, LLE, Univ. Rochester, NY, 25-27 April 2018.

T.S. Lane, P.M. Kozlowski, G.P. Loisel, M.K. Flaugh, J. E. Bailey, G. A. Rochau, M.E. Koepke, "Experimental development of isoelectronic line ratios in soft x-ray absorption spectra as a temperature diagnostic on Z" (contributed poster), Omega Laser User Group meeting, LLE, University of Rochester, Rochester, NY, 26-28 April 2017.

T. Lane. M. Flaugh, M. Koepke, T. Steinberger, G. Loisel, G. Rochau, J. Bailey, "Improving the fidelity of interpreting time-averaged spectra on Z for development of a multi-element Stark-broadening diagnostic" (contributed poster), Omega Laser User Group meeting, LLE, University of Rochester, Rochester, NY, 27-29 April 2016. Ted Lane won Honorable Mention for this poster presentation.

T. Steinberger, T. Lane. M. Flaugh, M. Koepke, G. Loisel, G. Rochau, J. Bailey, "Corroborating iso-electronic and iso-element spectral line diagnostics for determining density and temperature with refined certainty" (contributed poster), Omega Laser User Group meeting, LLE, Univ. Rochester, Rochester, NY, 27-29 April 2016.

T. Lane, M. Flaugh, M. Koepke, G. Loisel, G. Rochau, J. Bailey, "Assessing LTE reference conditions in photoionized-plasma experiments using a NaF-foil target to resolve charge-state-distribution discrepancies between models" (contributed poster), 3rd Conference on Radiation from High Energy Density Plasmas, South Lake Tahoe, CA, 9-12 June 2015.

M. Flaugh, T. Lane, M. Koepke, G. Loisel, G. Rochau, J. Bailey. "Distinguishing the spatial and temporal properties of proximity local-hardware thermal re-emission from the direct z-pinch emission in photo-ionized plasma experiments" (contributed poster), 3rd Conference on Radiation from High Energy Density Plasmas, South Lake Tahoe, CA, 9-12 June 2015.

T. Lane. M. Flaugh, M. Koepke, G. Loisel, G. Rochau, J. Bailey, "Establishing LTE reference conditions for photo-ionized plasma experiments using thick tamped sodium-fluoride foil target" (contributed poster), Omega Laser User Group meeting, LLE, Univ. Rochester, Rochester, NY, 15-17 April 2015. Ted Lane won Honorable Mention for this poster presentation.

M.K. Flaugh, T.S. Lane, M.E. Koepke, G.P. Loisel, G.A. Rochau, J.E. Bailey, T. Nagayama, "Distinguishing the proximity local-hardware thermal re-emission from the direct Z-pinch emission in photo-ionized plasma experiments" (contributed poster), Omega Laser User Group meeting, LLE, Univ. Rochester, Rochester, NY, 15-17 April 2015.

G. Loisel, J.E. Bailey, S.B. Hansen, T. Nagayama, G.A. Rochau, D. Liedahl, R. Mancini, M. Koepke, "X-ray line formation in radiation dominated astrophysical plasmas" (contributed oral, JO5.00014), Annual Meeting of the APS Division of Plasma Physics, New Orleans, LA, 26-31 October 2014.

T. Lane, M. Flaugh, M. Koepke, G. Loisel, G. Rochau, J. Bailey, D. Liedahl, D. Winget, R. Mancini, "West Virginia University's contributions to the Z Astrophysical Plasma Properties (ZAPP) project on Sandia's Z facility" (contributed poster), 2nd User Workshop on High Power Lasers, Stanford University, 7-8 October 2014.

Unexpended funds

The grant is fully expended.